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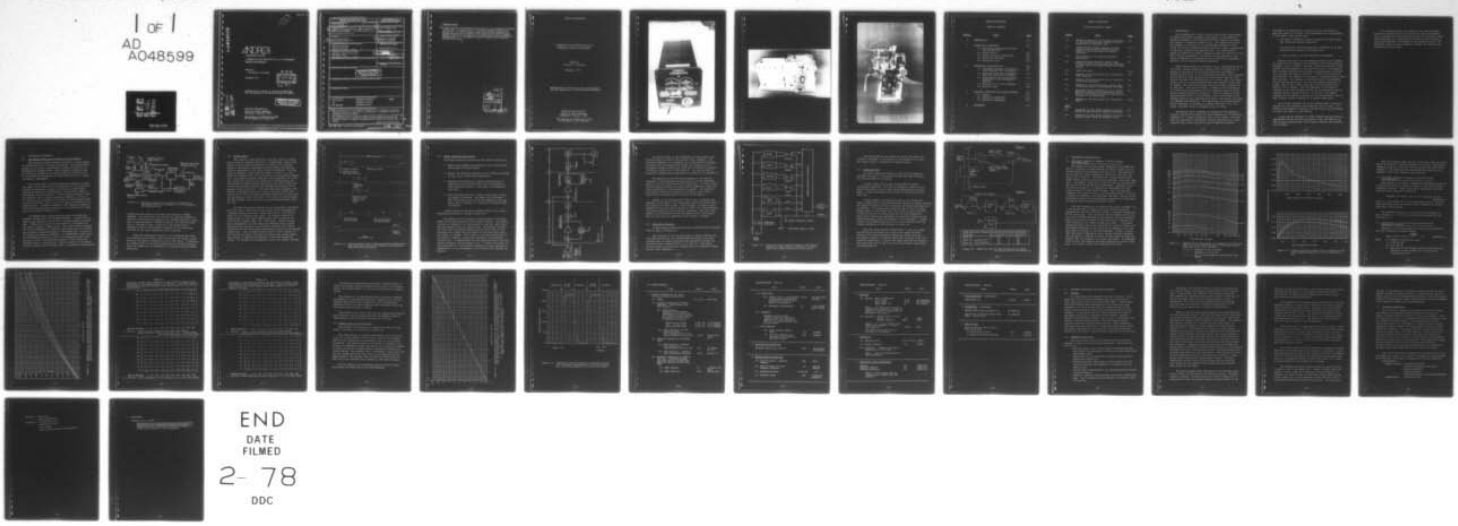

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INSTRUMENTS FOR LIFE

A SENSOR FOR THE DETECTION OF CO_2 IN HYPERBARIC GASEOUS ENVIRONMENTS

ARFR-105

By Kevin G. Williams

December 1977

Research Sponsored By:

OFFICE OF NAVAL RESEARCH
Arlington, Virginia 22217

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The characteristics of the essential components of a Nondispersive Infrared (NDIR) gas sensor for measuring CO_2 concentrations in hyperbaric gaseous environments have been studied.
The technique used is to subject a known volume of sample gas to a periodic density modulation and to measure the amount of CO_2 present by observing the fractional change in a beam of infrared radiation transmitted through that volume.

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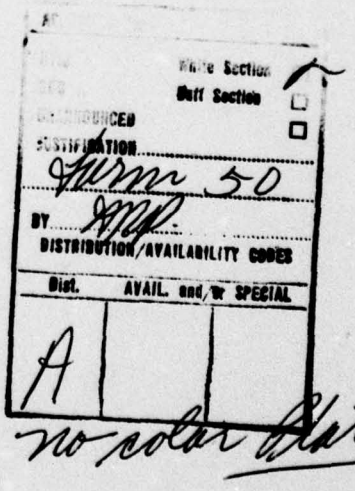
Abstract (Cont'd)

A sensor that uses this technique has been built for use in habitats at pressures up to 600 psia. It measures 8 x 7 x 14 inches and operates directly from 28 volts DC. The sensor's response is not strongly pressure dependent (the maximum deviation from the response at 14.7 psia being only 18% of reading). Neither re-zeroing nor recalibration are necessary since the design inherently maintains both. 0 to 90% response is about 40 seconds for both increasing and decreasing pCO_2.



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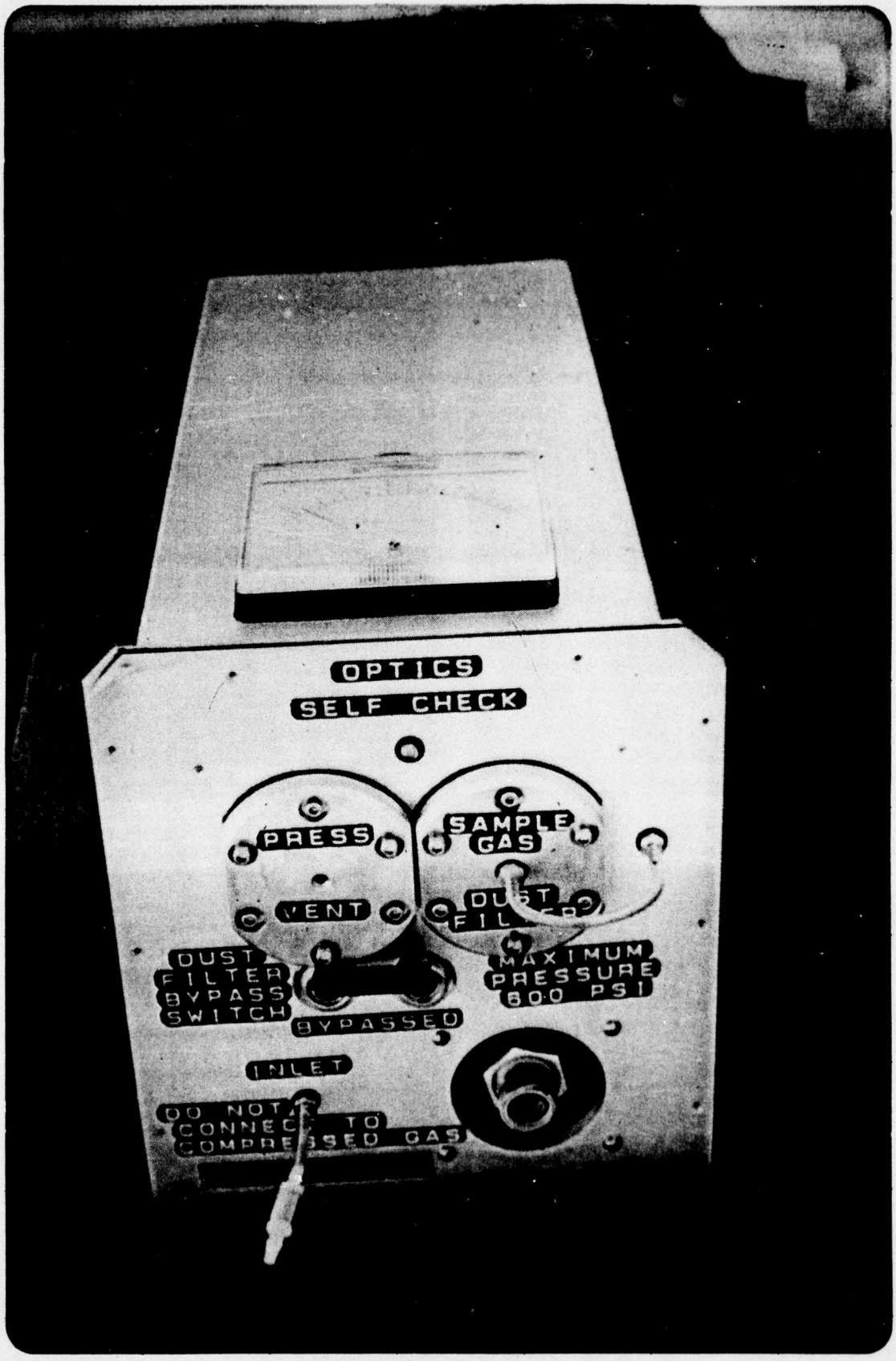
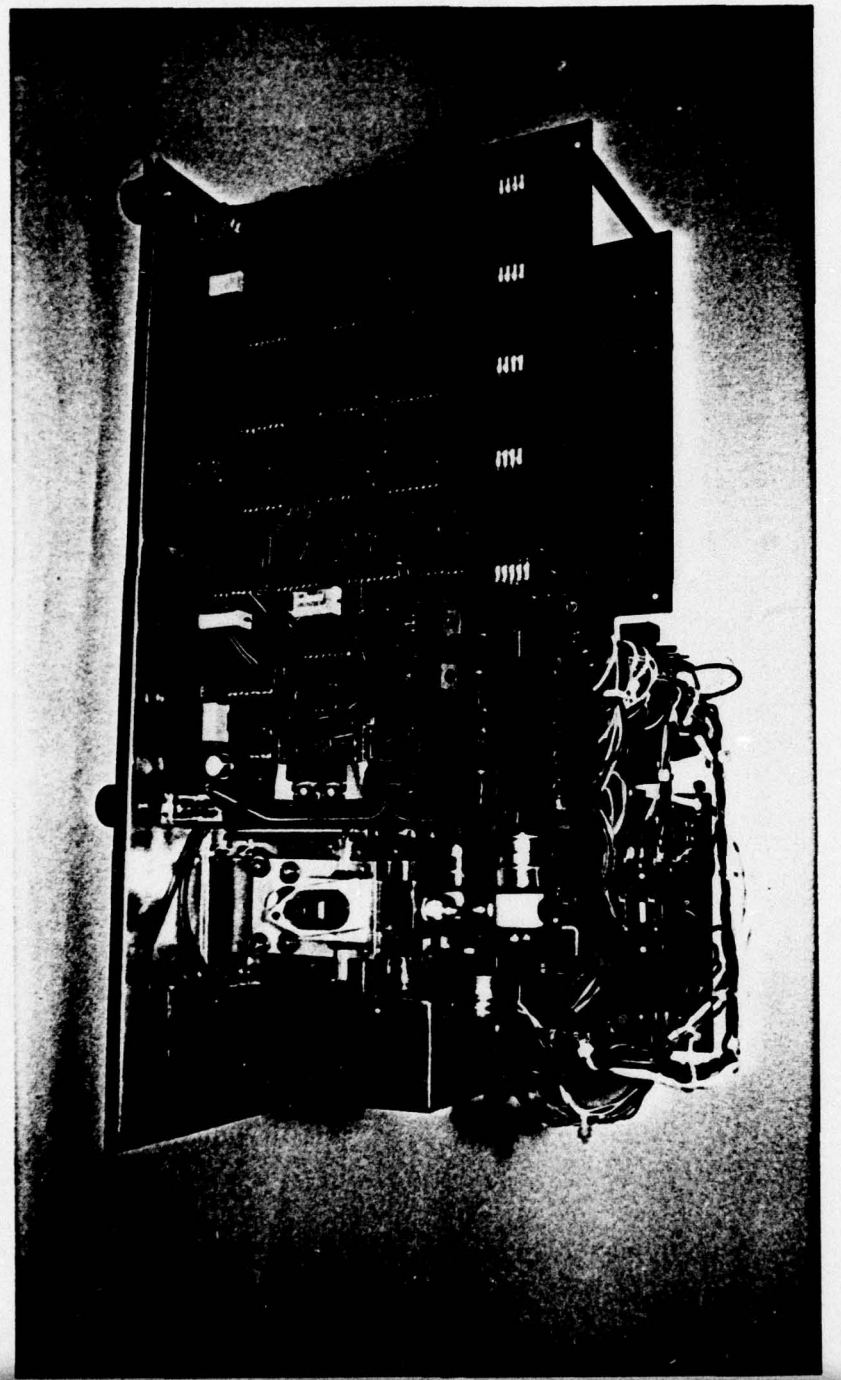

OPTICS
SELF CHECK
PRESS
SAMPLE GAS
VENT
DUST FIL
DUST FILTER BYPASS SWITCH
BYPASSED
MAXIMUM PRESSURE 600 PSI
INLET
DO NOT CONNECT TO COMPRESSED GAS



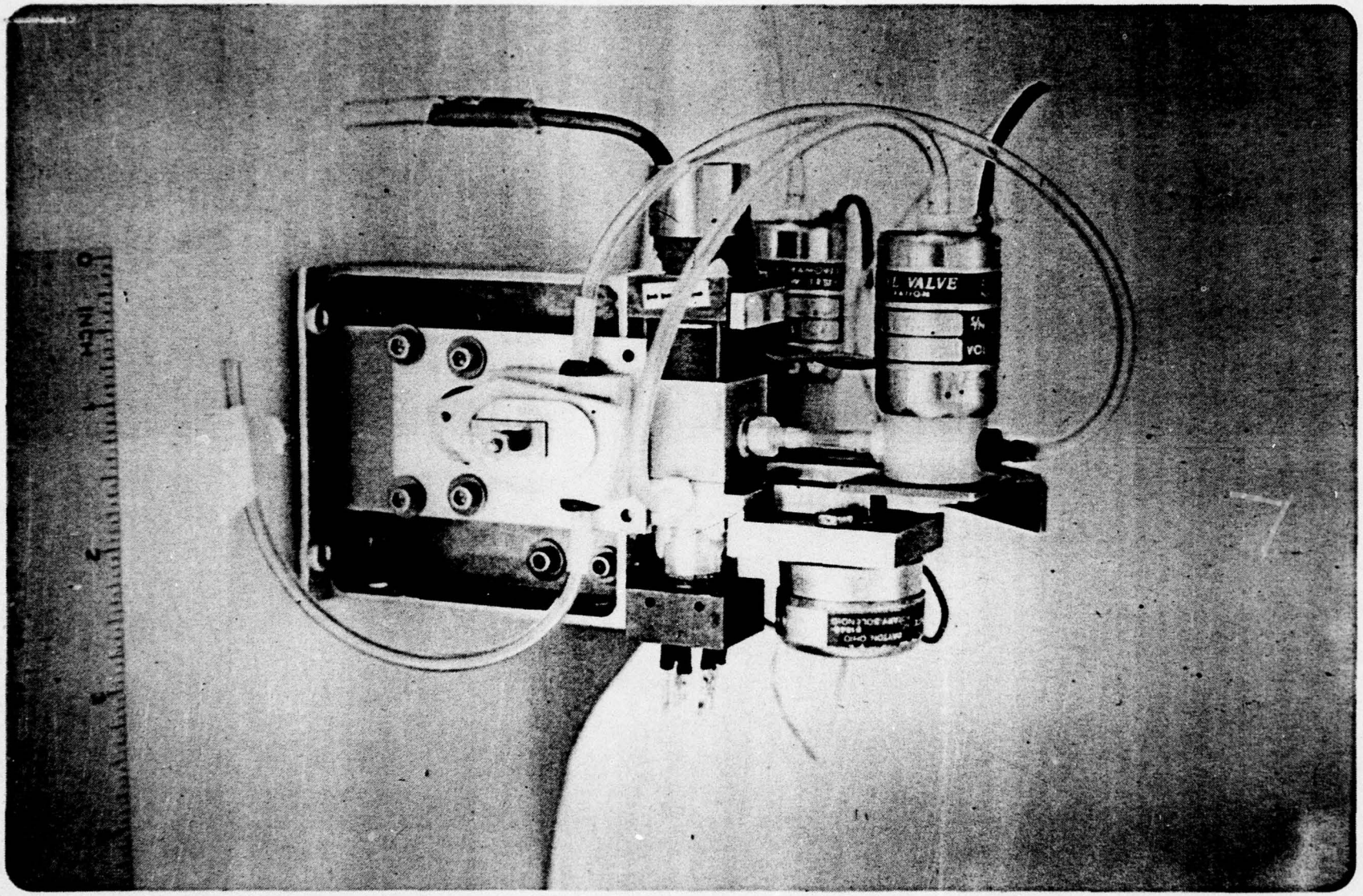

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

1. INTRODUCTION

The development of a small, accurate and reliable alarm sensor to monitor the partial pressure of CO_2 (pCO_2) in the hyperbaric gaseous environment of the saturation diver is required to prevent his exposure to dangerous levels of CO_2. Such exposure may occur, for example, in the event of an unpredictable decrease in efficiency of the CO_2 scrubbing material required to prevent accumulation of the CO_2 released in the expired breath. The sensor must be capable of operating at depths possibly as great as 2700 feet in sea water (which corresponds to a pressure of about 1200 psia), and should be adaptable to extended periods of operation in hyperbaric habitats, and in Personnel Transfer Capsules.

Andros Incorporated has developed a novel, nondispersive infrared (NDIR) "density modulation" technique that is believed to be capable of meeting all the previously mentioned requirements. Supporting this belief is an investigation (Williams, 1973) sponsored by the Office of Naval Research which demonstrated that the technique is suitable for measuring pCO_2 up to 10 mm, with a zero error of less than 0.1 mm pCO_2 equivalent and time response of less than 40 seconds, while maintaining good accuracy for total pressures up to 1200 psia. Using this technique, a sample of gas is subjected to a known density modulation and the fractional change in transmitted infrared radiation is measured. Since the radiation is not modulated when there is no CO_2 present, then at such times an instrument based on this technique will yield a zero output, and hence has INHERENT ZERO STABILITY. This application of the density modulation technique is the basis of a patent (Williams, K.G., U.S. Patent 3,922,551) which is assigned to the U.S. Navy.

The present report documents the findings of the subsequent contract from ONR to determine the characteristics of the essential components of a density modulation type of pCO_2 sensor. This program has culminated in the design, building and testing of a self-contained pCO_2 sensor that may be used in hyperbaric gaseous

environments at pressures up to 600 psia, and is calibrated to read pCO_2 levels up to 10 mm. Three photographs (at the beginning of this report) show respectively:

- the sensor's enclosure on which is mounted the meter read-out, electrical and gas connections.

- the electronics and opto-mechanical subassembly in the configuration used within the enclosure, and

- a close up view of the opto-mechanical subassembly.

Testing this sensor over the complete range of total pressure has shown that its response first increases (as the total pressure increases) until it reaches a maximum at about 50 psia that is 18% greater than the response at sea level (14.7 psia). The response then decreases monotonically at higher pressures until at 600 psia it is 5% below its value at sea level. If the total pressure is held constant, the response of the sensor to increasing pCO_2 is somewhat nonlinear. For example, if the sensor were to be calibrated to read the correct pCO_2 at 4 mm, and the response assumed to be linear, then for pCO_2 levels less than 8 mm, the maximum error would be 15% of reading. Both the dependence of the sensor's response on the total pressure as well as its nonlinearity can be corrected using a single relation. In this way, the sensors response may be tailored to provide the (fully corrected) level of pCO_2 directly (in mm of mercury) on a digital panel meter.

The 0 to 90% response time of the present sensor is about 40 seconds for both increasing and decreasing levels of pCO_2. If a shorter time response is required, then the design can be modified to reduce this down to a few seconds.

IT WILL NOT BE NECESSARY TO EITHER READJUST THE ZERO POINT OR RECALIBRATE THE SPAN OF THIS pCO_2 SENSOR, SINCE THE STABILITY OF BOTH OF THESE CONTRIBUTIONS TO THE SENSOR'S ACCURACY ARE INHERENT IN ITS DESIGN.

It is anticipated that the sensor that has been developed during the present contract will provide the Navy with hardware that is suitable for evaluating the viability of the density modulation technique for continuously monitoring the level of CO_2 in the gaseous hyperbaric environment of the saturation diver. An instrument manual has been prepared to support the operation and maintenance of this sensor.

2. PRINCIPLES OF OPERATION

2.1 The Density Modulation Technique for Gas Detection

Most molecules absorb infrared radiation at various groups of wavelengths which are unique to each gas. The present sensor belongs to the class of gas analyzers commonly referred to as NONDISPERSIVE INFRARED (NDIR), which identify a particular gas by looking for absorption of infrared radiation by most or all of the individual absorption lines which make up one of a group (or BAND) of wavelengths.

This sensor uses a "density modulation" technique in which the number of CO_2 molecules in the radiation path is varied periodically by subjecting a sample of the gas to a known number density modulation and then measuring the fractional change in transmitted infrared radiation. A more complete account of NDIR gas detection and the density modulation technique, as well as the effect of total pressure on the shape of the absorption LINES, is given by Williams (1973), and only a brief description will be presented here. A schematic drawing of the essential components of this density modulation analyzer as it is configured for hyperbaric use is shown in Figure 2.1.

An INFRARED source emits radiation which is transmitted through a SAMPLE CELL to an INFRARED DETECTOR. A SAMPLE PUMP is used to draw samples of the gas to be analyzed through the SAMPLE CELL. VALVES on the inlet and outlet ports of the SAMPLE CELL are used to isolate a sample of gas. This fixed volume of sampled gas is then subjected to a constant volume modulation by compressing a bellows (connected directly to the SAMPLE CELL) by means of an electric motor-driven ECCENTRIC. An INTERFERENCE FILTER limits the transmitted radiation to that of the strong absorption band of CO_2 at 4.25μm. The modulated component of the transmitted radiation (which is produced by a regular variation of the number of CO_2 molecules in the radiation path) is obtained by synchronously

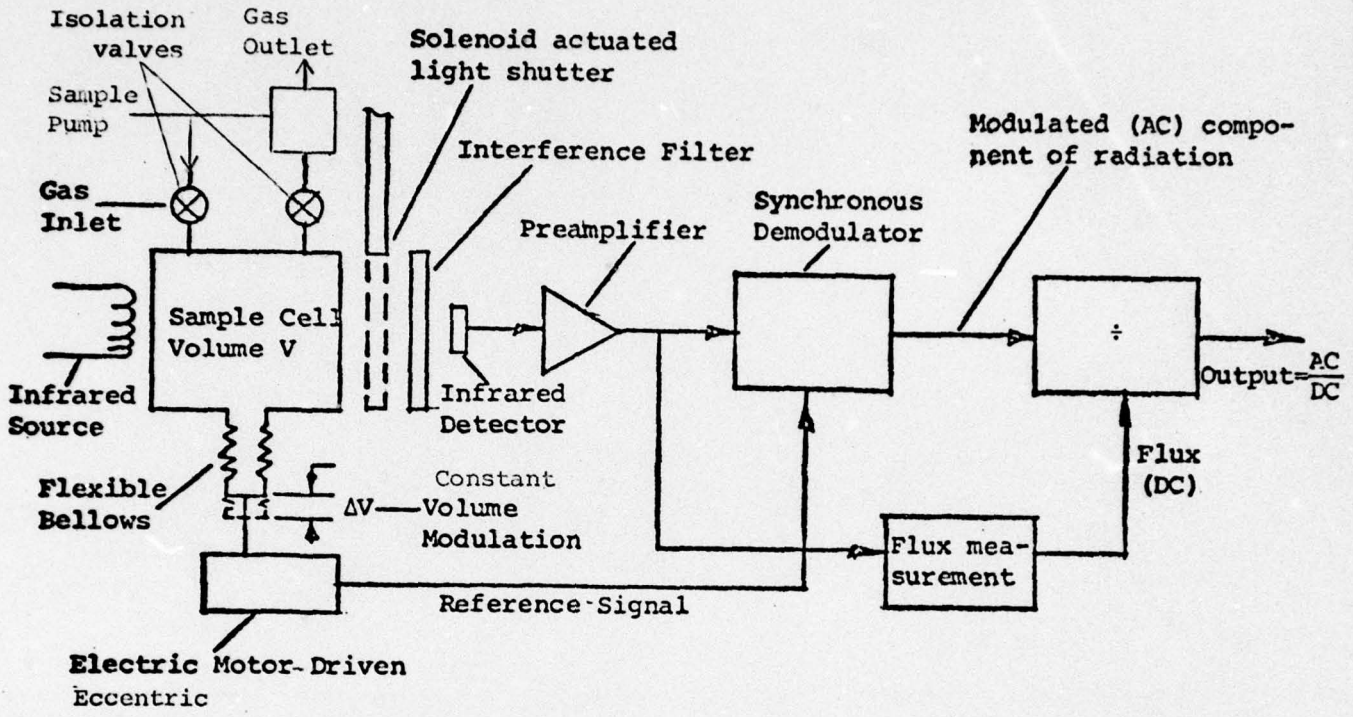


Figure 2.1. Schematic drawing of the essential components of the density modulation analyzer as it is configured for hyperbaric use.

demodulating the output of the PbSe (Lead Selenide) INFRARED DETECTOR. The total light flux reaching the INFRARED DETECTOR is measured by monitoring the change in the INFRARED DETECTOR'S output when a solenoid-operated SHUTTER interrupts the radiation momentarily. The pCO_2 is then a function of the electronically determined ratio of the modulated component of the transmitted radiation to the total transmitted (flux) radiation.

Since the transmitted radiation is not modulated when there is no absorbing gas present, then at such times the output is zero and hence the sensor is inherently free of zero drift. In addition, the sensor's span is relatively insensitive to the total pressure, since the sampled gas is subjected to a constant fractional volume modulation.

2.2 System Timing

Some aspects of the operation of the pCO_2 sensor are analogous to that of a digital volt meter. In particular, while a new sample is being taken and measured, the value of the previous sample is continuously displayed--and only updated periodically when the measurement of the latest sample is completed. The pCO_2 sensor's sequence of time intervals (shown in Figure 2.2) into which the complete cycle (T) is divided may be conveniently grouped into a gas sampling interval (TS) and a gas measurement (T4) interval. During the time that the sample gas is being changed, the solenoid-driven shutter blocks the optical path (time interval T1) so that the infrared radiation flux reaching the detector can be measured (time interval T2). The span stabilizing (automatic gain control) electronics locks in at the new flux level during time interval T3 so that the signal processing electronics is ready when the gas sampling valves are closed. The readout is updated during the time interval T5 at the end of the gas measurement time interval (T4).

The time intervals T1 through T4 are independently selectable and T5 is fixed. Time intervals T1 through T4 are determined by 4 separate counters that use a common clock pulse. The time interval T5 is a complete clock cycle. The counters function by counting down to zero from a preset number that is reset at the start of each complete cycle (T). This preset number is determined independently for each counter by hardwired binary inputs. Successive time intervals are obtained by enabling each counter (other than for T1) from another (preceding) counter that has already reached zero. Thus T1 enables both T2 and T3, and T3 enables T4. DIP switches are used to determine the preset count during laboratory testing to simplify the selection of the most appropriate values. The switches are subsequently removed and jumpers inserted.

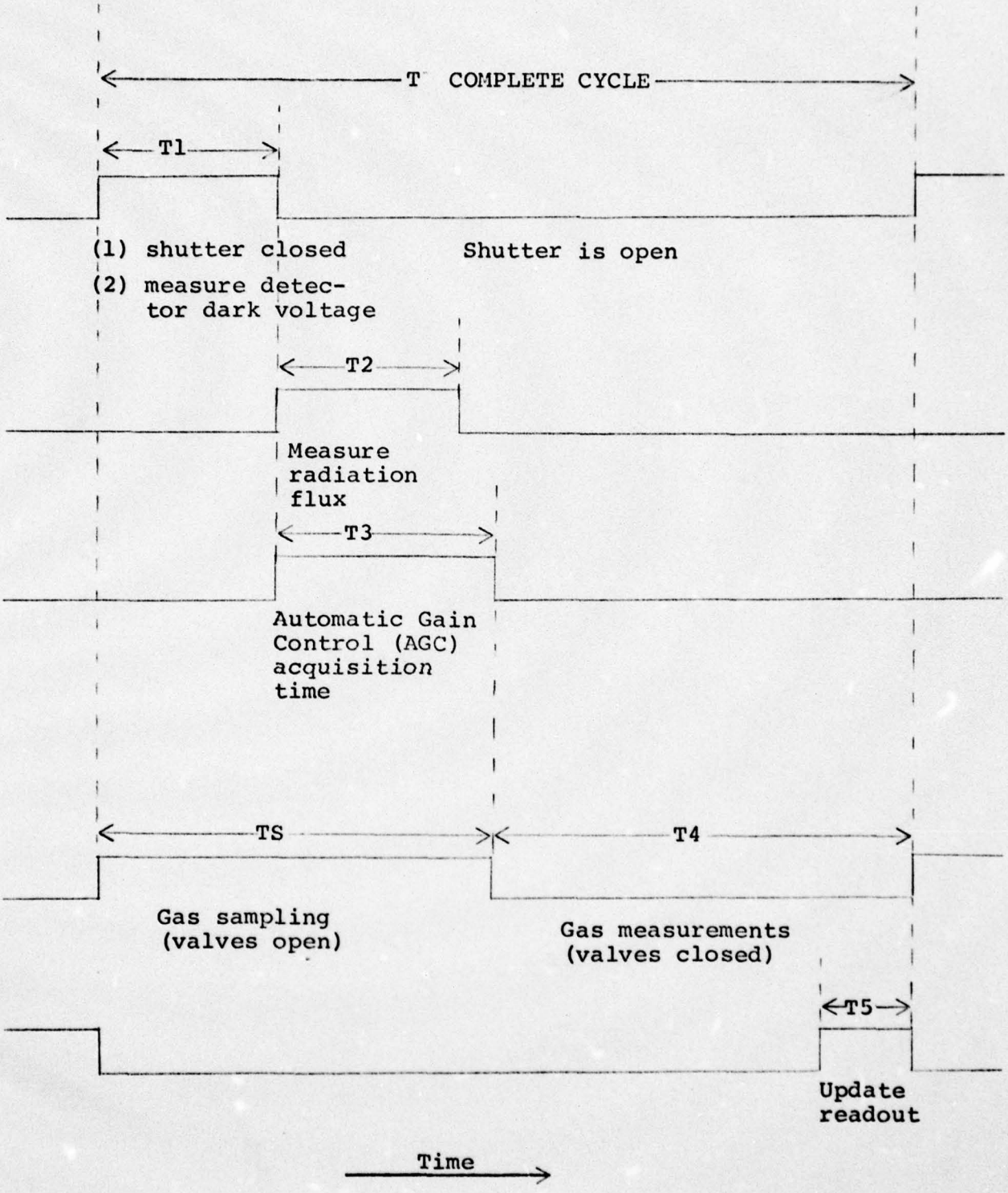


Figure 2.2. Timing sequence diagram showing the basic timing intervals which determine the gas sampling, pCO_2 measurement and readout functions.

2.3 Signal Processing Electronics

The signal processing electronics uses analog circuitry to:

1. Measure and remember the magnitude of the infrared flux, using sample and hold modules.

2. Measure the modulated component of the radiation absorbed by CO_2, using a synchronous demodulator.

3. Determine the fraction of infrared radiation that is absorbed by CO_2 by deriving the ratio of modulated to total infrared radiation. This value is calibrated to read pCO_2.

4. Store the pCO_2 value for a sample of gas while a fresh gas sample is measured. The sample and hold module that stores this value is read continuously on the pCO_2 meter, and is available as a voltage for external read-out devices.

A block diagram of the major building blocks of the signal processing electronics is given in Figure 2.3.

The radiant flux is measured as follows using a DC-coupled buffer to the photoconductive PbSe infrared detector. The voltage at point B in Figure 2.3 is first driven to zero by a servo loop when the shutter blocks the optical path. The current injected at this time into the summing junction A by the servo loop is then maintained by a sample and hold module (in the servo loop) after the shutter is removed. The voltage at B is then proportional to the change in detector voltage and, therefore, to the detected infrared flux. A second sample and hold module maintains this flux voltage throughout the measurement cycle. A square wave signal is then generated at a "flux chopper" frequency f_2 whose amplitude is proportional to the DC component of the infrared flux reaching the detector.

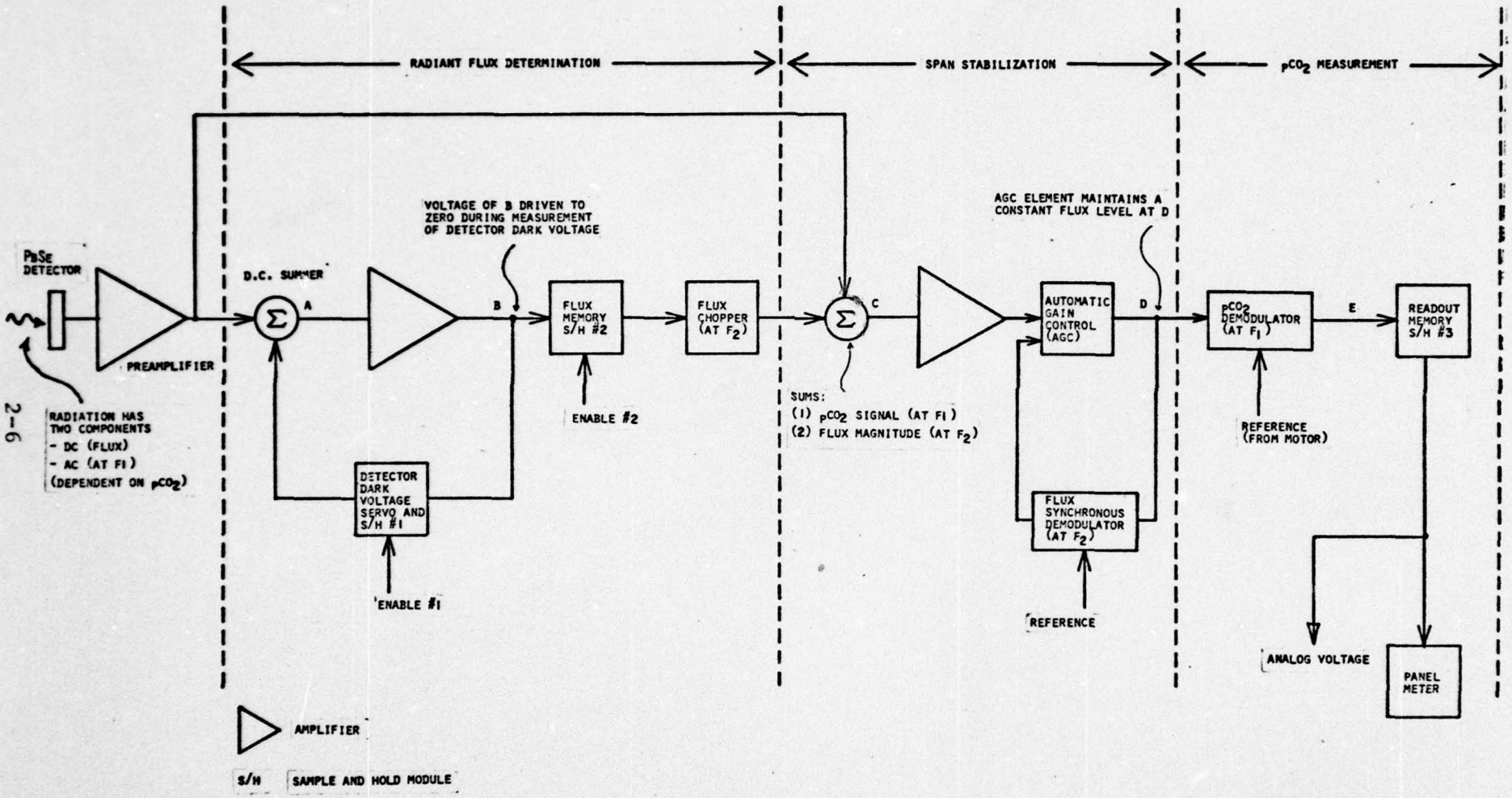


FIGURE 2.3. BLOCK DIAGRAM OF THE SIGNAL PROCESSING ELECTRONICS.

The measured pCO_2 is made independent of the infrared flux level by using an automatic gain control (AGC) subsystem. The modulated component (at a frequency f_1) of the absorbed radiation is summed with the infrared flux signal (at frequency f_2) at C and passed through an AGC element whose gain is servoed to maintain a constant infrared flux at the output D. The infrared flux is measured by synchronously demodulating the output D at frequency f_2.

The magnitude of the modulated component of the absorbed radiation is then determined by demodulating the span stabilized output (D) at the volume modulation frequency f_1. A (third) sample and hold module preserves the time-averaged demodulator output (E) during measurement of the subsequent gas sample. The voltage on this sample and hold is available for external readout and is used to drive the pCO_2 meter on the case of the sensor.

Because of the preamplifier's high AC gain, transients are produced at the output of the preamplifier when the shutter blocks and unblocks the optical path. This transient is sensed by level crossing circuits and used to operate a "self test" which indicates the correct operation of the optical components. The "self test" output is an LED mounted on the front panel which flashes either once or twice each gas measurement cycle (about 10 seconds).

2.4 Electrical Isolation

A block diagram summarizing the major power/grounding considerations is given in Figure 2.4.

The (nominal) 28 volt DC input power is used to operate the 2 solenoid gas valves, the solenoid-operated shutter, the motor (driving both the sample pump and volume modulating bellows) and 2 DC-to-DC power converters (for $\pm$ 15 V and 5 V). The return for this power is electrically isolated from the instrument chassis and all other components.

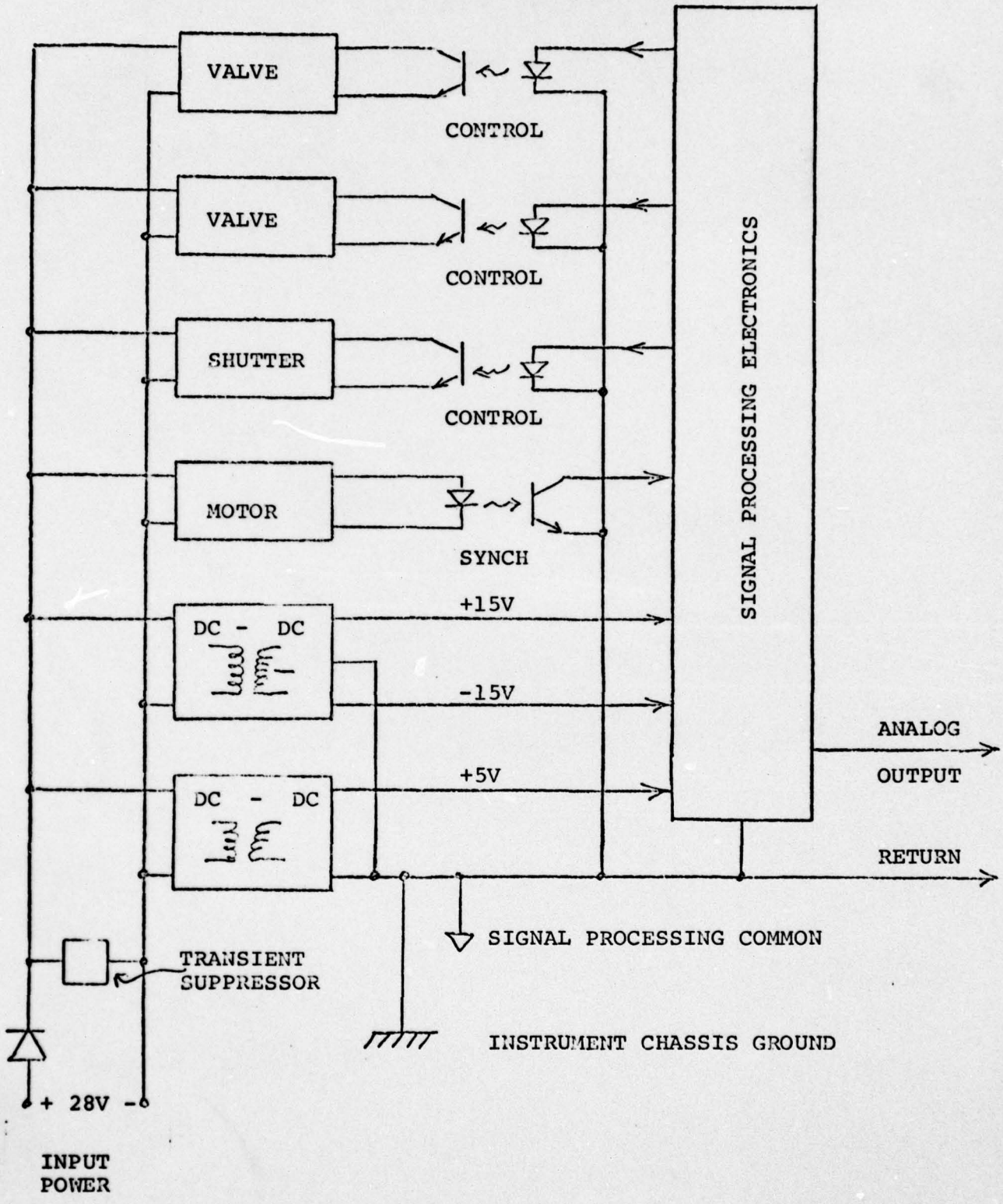


Figure 2.4. Electrical power grounding showing items powered directly by input power and isolation of input power from chassis ground and analog output.

The return side of the outputs of the DC-to-DC power converters is grounded to the chassis at the preamplifier so that the analog output is referenced to chassis ground.

2.5 Sample Gas Flow

The major conditions relating to the flow of sample gas are shown in Figure 2.5 and may be divided into dust filtering and flow switching at the optics.

A large capacity dust filter is provided for normal (continuous) operation. This may be bypassed to reduce the response time using the dual 3-way valves operated from the front panel. A small low capacity dust filter is included in the bypass line.

A sample pump on the downstream side of the sample cell draws a stream of gas which either passes through the sample cell when the solenoid valves are open, or bypasses the sample cell when this is isolated. The sample pump exhaust is used to purge the small "dead volume" in the optical path that houses the optical shutter so that all gas in the optical path has the same composition. This feature removes the dependence of instrument response on the (uncontrolled) pCO_2 inside the cabinet of the instrument. A table listing the through-connections of the 3-way solenoid valves for various conditions is also included in Figure 2.5.

Note that large pressure differentials between the inside and outside of the sample cell (which could damage the metal bellows of the volume modulation mechanism) cannot build up if the ambient pressure is changed widely when the power is off, because the sample cell is open to the sample pump and the design of the pump allows gas to leak in or out to equilibrate static pressure differentials.

Figure a

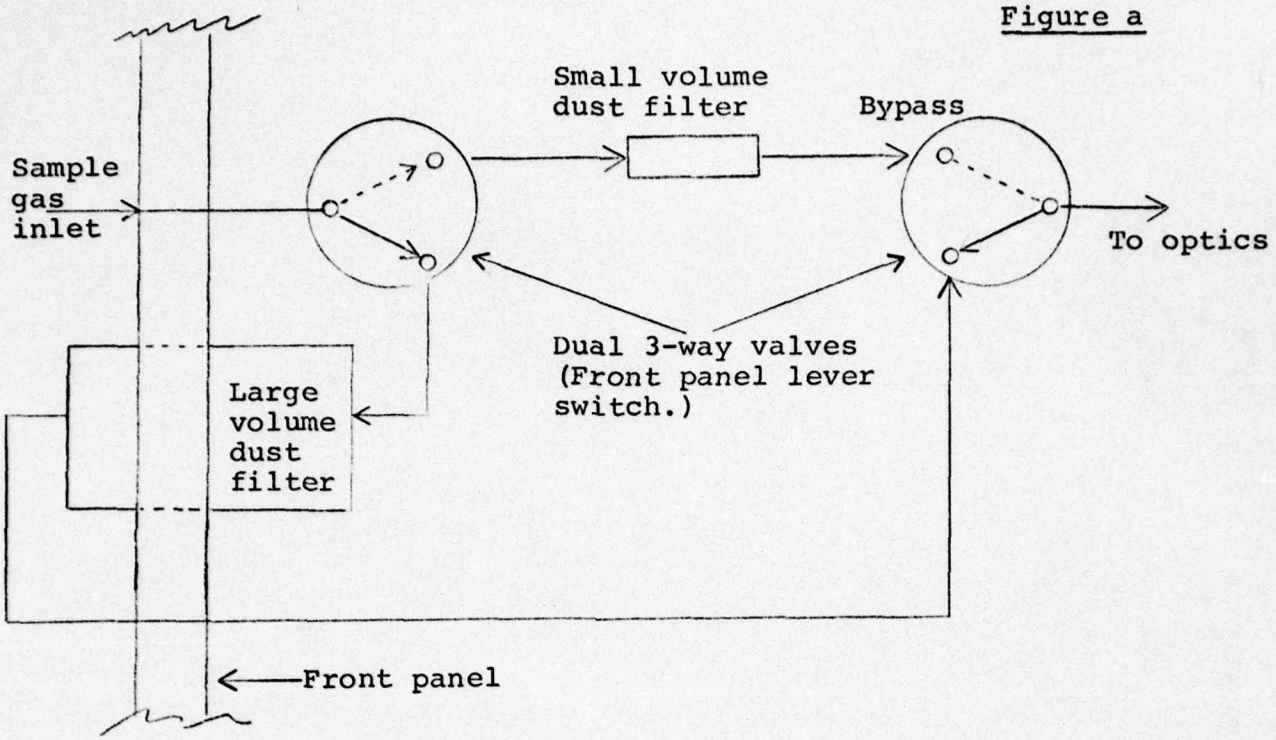
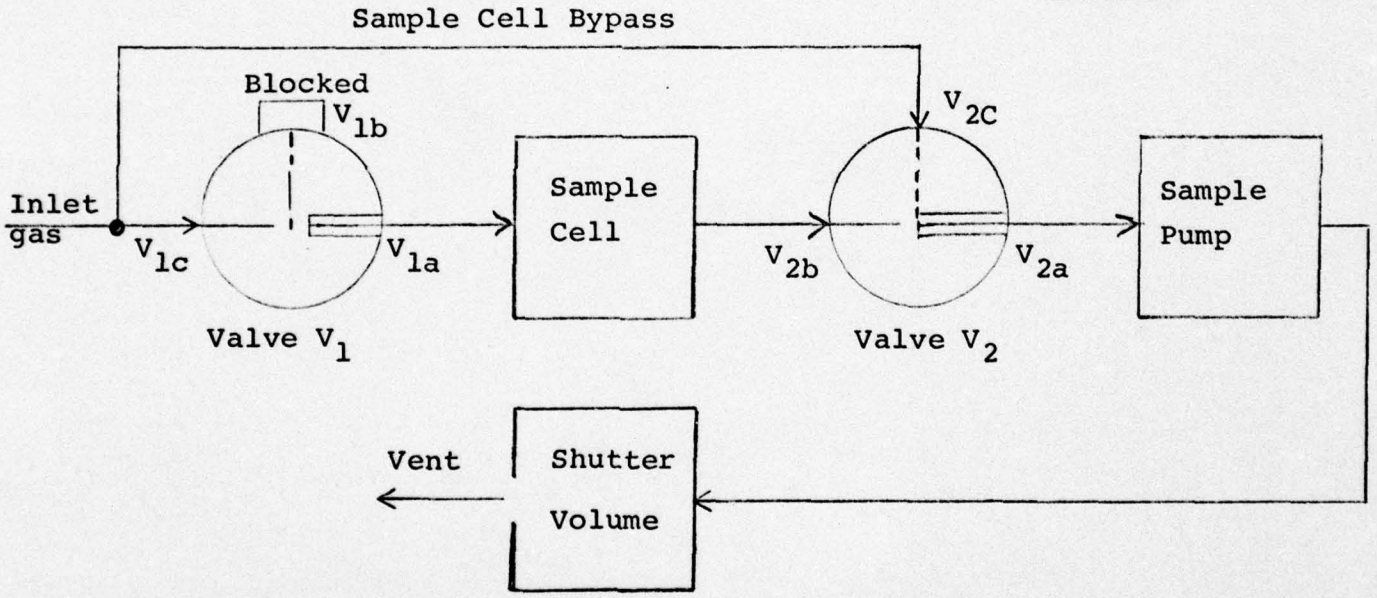


Figure b



3-Way valve port through-connections for various conditions		
Condition	V_{1a} connected to	V_{2a} connected to
Power off	V_{1b}	V_{2b}
Power ON - sampling gas	V_{1c}	V_{2b}
Power ON - cell isolated	V_{1b}	V_{2c}

Figure 2.5. Sample Gas flow (a) dust filters and switching
(b) solenoid valves and sample cell

3. PERFORMANCE CHARACTERISTICS

3.1 Instrument Response to Changes in Total Pressure (For Fixed pCO_2)

The response of the pCO_2 sensor (measured at the ANALOG OUTPUT) as a function of total pressure is shown in Figure 3.1 for various values of pCO_2 between 0.25 and 9.6 mm. The response to CO_2 is shown for total pressures of helium up to 600 psia, and for air up to 100 psia. The sensor has a small negative zero offset (whose origin is unknown) which increases with total pressure. For example, a pCO_2 of 0.50 mm will read low by about 0.05 and 0.10 mm at 100 and 600 psia respectively. Additional lines are shown on Figure 3.1 to indicate the contribution of this source of error at lower levels of pCO_2. Note also that the response of the sensor to CO_2 in air is greater than it is to CO_2 in helium for pressures less than about 100 psia. This is due to differences between the thermodynamical properties of helium and air and has been discussed by Williams (1973).

From the similarity of the shape of the curves in Figure 3.1, it can be seen that a change in the total pressure produces approximately the same fractional change in response--irrespective of the actual pCO_2. Thus two curves (one for helium and one for air) can be derived (designated the Pressure Correction Factor D), which may be used to correct for the variation in response with total pressure at all levels of pCO_2 up to 10mm. The Pressure Correction Factor curves for helium and air (given in Figure 3.2) correspond essentially to the variation in response of a 4.2 mm pCO_2 sample to changes in the total pressure. Figure 3.2 shows that the sensor's response to CO_2 in helium initially increases with pressure to a maximum (at about 50 psia) which is about 18% greater than the response at 14.7 psia (sea level). At pressures about 50 psia, the response decreases monotonically until at 600 psia, it is about 5% below the response at 14.7 psia.

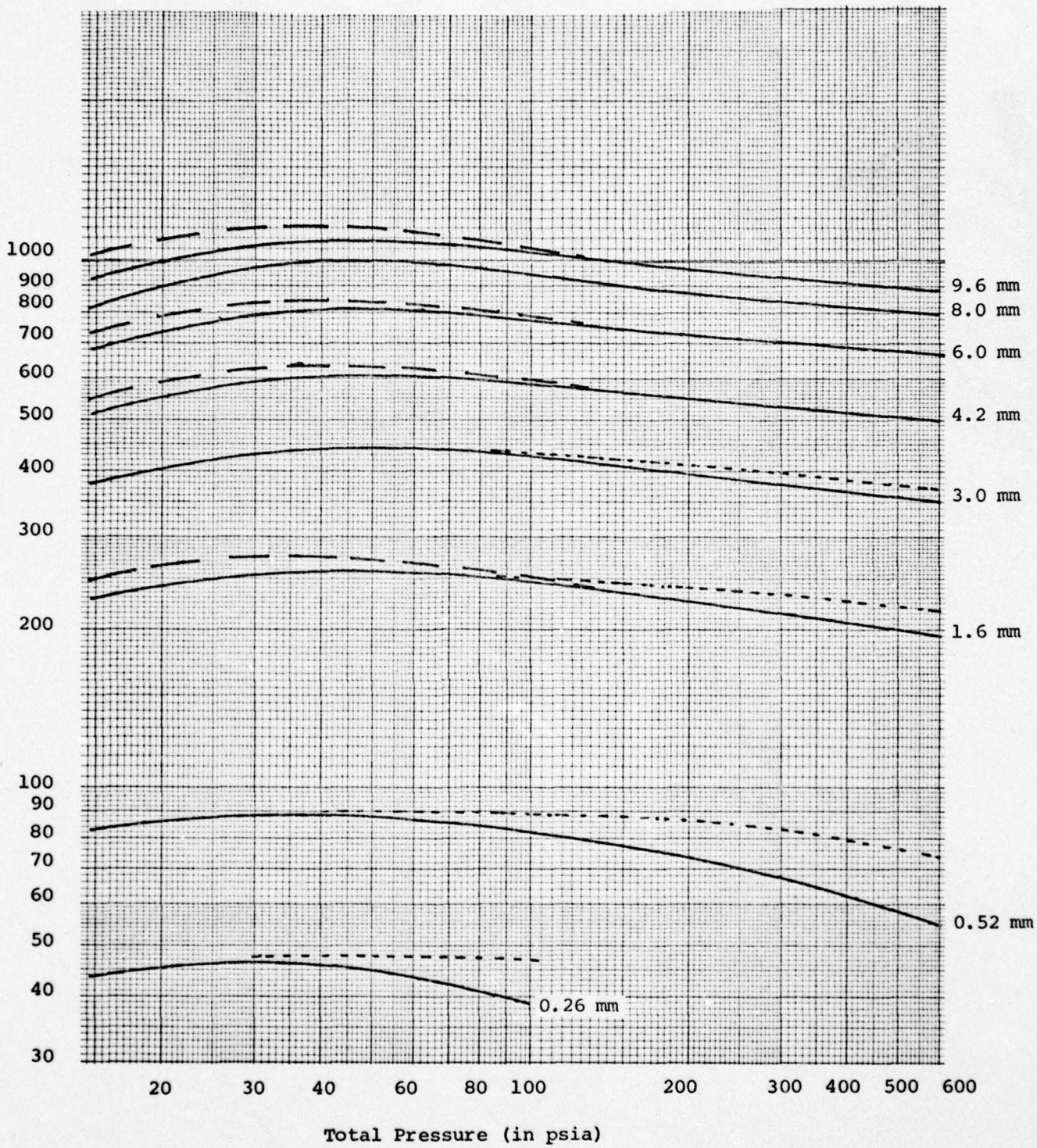


Figure 3.1. Response of the pCO_2 sensor as a function of total pressure for various values of pCO_2 in helium (up to 600 psia) and in air (up to 100 psia).

———— Response to CO_2 in helium.

- - - - - Response to CO_2 in air.

..... CO_2 in helium response corrected for zero offset.

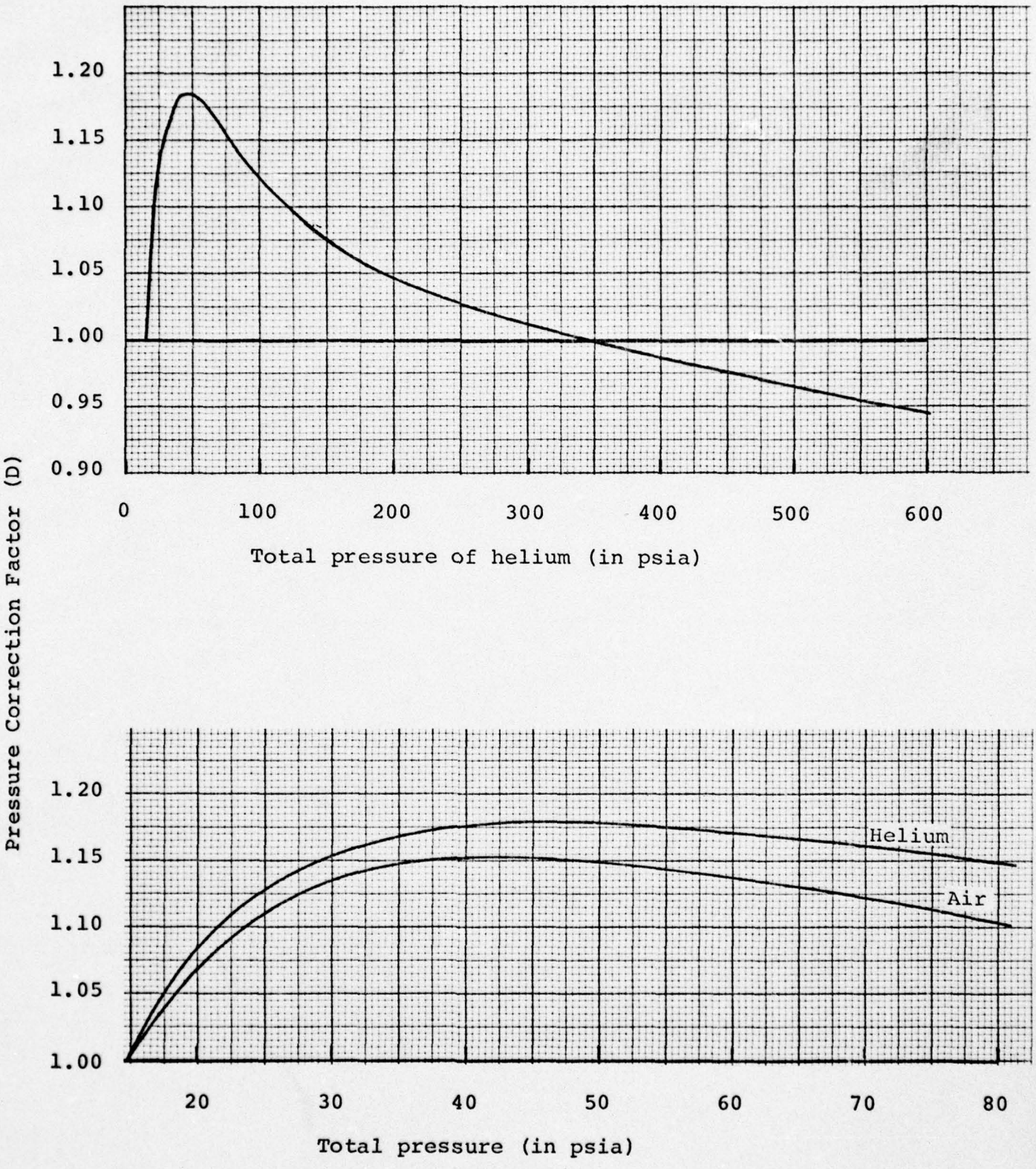


Figure 3.2. Pressure correction factor (D) as a function of the total pressure pressure for CO_2 in helium and in air.

Over the pressure range from 200 to 600 psia, there is a maximum of 5% deviation from the response at 14.7 psia. The sensors response to CO_2 in air follows the same general character as its response to CO_2 in helium--with the maximum deviation from its response at 14.7 psia, however, being only 15%.

3.2 Instrument Response to Changes in pCO_2 (For Fixed Total Pressure)

The response of the sensor (measured at the ANALOG OUTPUT) as a function of the pCO_2 is shown in Figure 3.3 for various total pressures of helium. These curves may be represented with good accuracy by the analytical expression:

$$\text{Response (in volts)} = G.D.\ln\,(1 + 0.16\ pCO_2\ (\text{in mm})) \qquad \text{Equation 3.1}$$

where G = 1 for helium and D is the particular value of the Pressure Correction Factor for helium (given in Figure 3.2) at the particular total pressure.

The response for CO_2 in air is also given by Equation 3.1 with, however, G = 1.07 for air and D must be selected for air from Figure 3.2.

3.3 Linearization and Total Pressure Correction of the Instrument's Response

Equation 3.1 can be rearranged so that pCO_2 can be derived from the instrument's response, namely

$$pCO_2\ (\text{in mm}) = 6.25\ (e^{\frac{V(\text{volts})}{G.D}} - 1), \qquad \text{Equation 3.2}$$

where V = sensor's response (in volts)
G = 1 for helium
G = 1.07 for air
D = the value of the Pressure Correction Factor at the particular total pressure for the type of gas (using Figure 3.2).

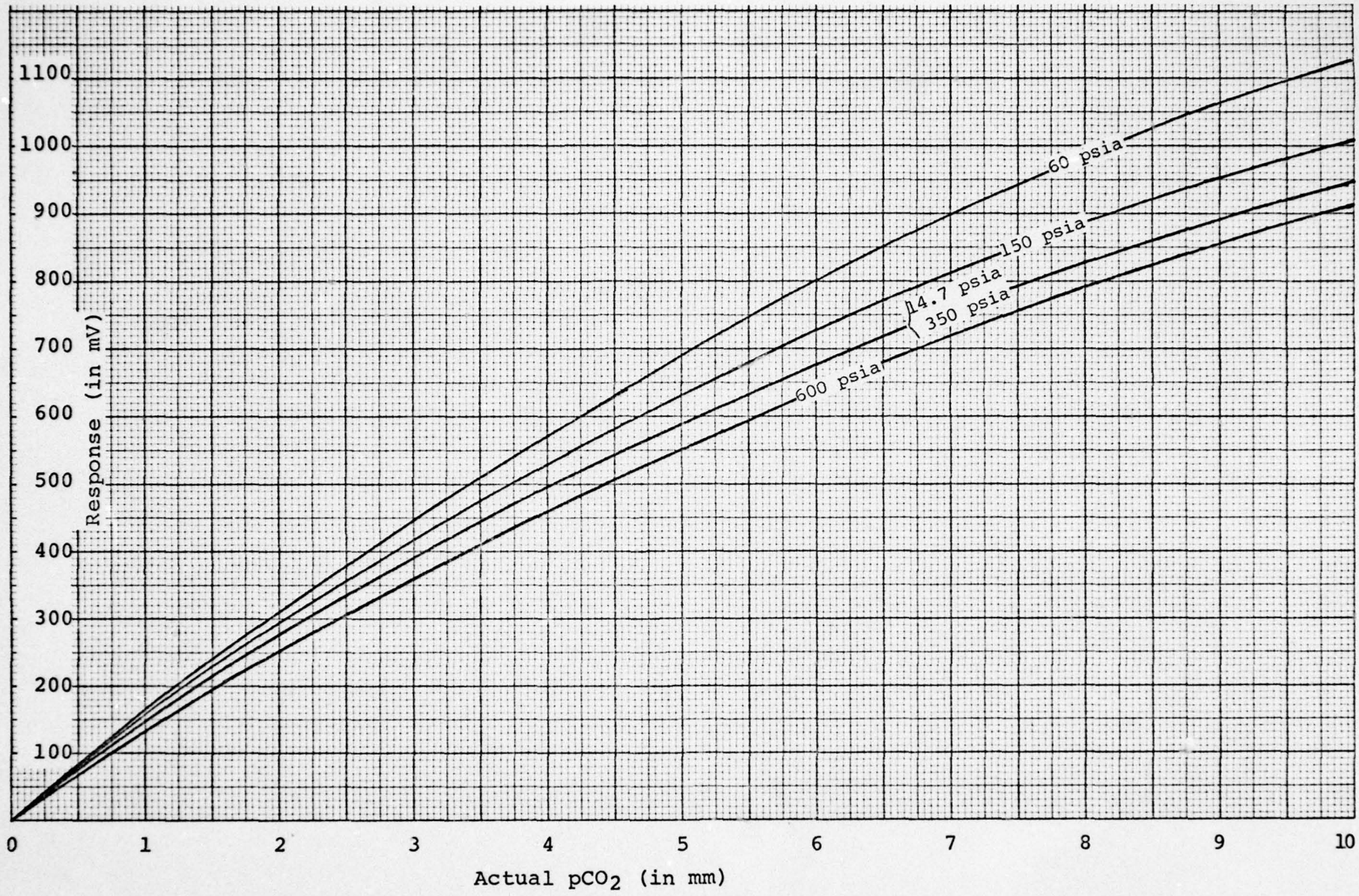


Figure 3.3. Response of the (unlinearized) ANALOG OUTPUT of the pCO_2 sensor as a function of the pCO_2 for various total pressures of helium. Note that the total pressures selected include both extremes of the sensor's response.

TABLE 3.1

Conversion of pCO_2 sensor response (in millivolts) to pCO_2 (in mm of mercury) in helium pressures up to 600 psia. The error resulting from dividing the total pressure into these ranges is ≤ (6% of reading + 0.1 mm).

90	0.6	1.3	2.1	3.0	4.0	5.0	6.2	7.5	9.0	10.6
80	0.5	1.2	2.0	2.9	3.9	4.9	6.1	7.4	8.8	10.4
70	0.5	1.2	1.9	2.8	3.7	4.8	6.0	7.2	8.7	10.2
60	0.4	1.1	1.9	2.7	3.7	4.7	5.8	7.1	8.5	10.1
50	0.3	1.0	1.8	2.6	3.6	4.6	5.7	7.0	8.4	9.9
40	0.3	0.9	1.7	2.5	3.5	4.5	5.6	6.8	8.2	9.7
30	0.2	0.9	1.6	2.4	3.4	4.4	5.5	6.7	8.1	9.6
20	0.1	0.8	1.5	2.4	3.3	4.3	5.4	6.6	7.9	9.4
10	0.1	0.7	1.5	2.3	3.2	4.2	5.3	6.5	7.8	9.3
0	0.0	0.7	1.4	2.2	3.1	4.1	5.1	6.3	7.7	9.1
SENSOR RESPONSE	0	100	200	300	400	500	600	700	800	900

a. Use for: Precise sensor reading at 14.7 psia (sea level)
Total pressures of 14.7 to 18 psia (0 to 7.5 feet depth.
200 to 600 psia (416 to 1314 feet depth.

90	0.5	1.2	1.9	2.6	3.5	4.4	5.4	6.5	7.7	9.0
80	0.5	1.1	1.8	2.6	3.4	4.3	5.3	6.4	7.6	8.9
70	0.4	1.0	1.7	2.5	3.3	4.2	5.2	6.3	7.4	8.7
60	0.3	1.0	1.6	2.4	3.2	4.1	5.1	6.1	7.3	8.6
50	0.3	0.9	1.6	2.3	3.1	4.0	5.0	6.0	7.2	8.5
40	0.2	0.8	1.5	2.2	3.0	3.9	4.9	5.9	7.1	8.3
30	0.2	0.8	1.4	2.2	3.0	3.8	4.8	5.8	7.0	8.2
20	0.1	0.7	1.4	2.1	2.9	3.7	4.7	5.7	6.8	8.1
10	0.1	0.7	1.3	2.0	2.8	3.6	4.6	5.6	6.7	7.9
0	0.0	0.6	1.2	1.9	2.7	3.6	4.5	5.5	6.6	7.8
SENSOR RESPONSE	0	100	200	300	400	500	600	700	800	900

b. Use for: Total pressures of 18 to 200 psia (7.5 to 416 feet depth).

TABLE 3.2

Conversion of pCO_2 sensor response (in millivolts) to pCO_2 (in mm of mercury) in air pressures up to 100 psia. The error resulting from dividing the total pressure into these ranges is ≤ (5% of reading + 0.1 mm).

90	0.5	1.2	1.9	2.7	3.6	4.6	5.7	6.8	8.1	9.5
80	0.5	1.1	1.9	2.7	3.5	4.5	5.5	6.7	8.0	9.4
70	0.4	1.1	1.8	2.6	3.4	4.4	5.4	6.6	7.8	9.2
60	0.4	1.0	1.7	2.5	3.4	4.3	5.3	6.5	7.7	9.1
50	0.3	0.9	1.6	2.4	3.3	4.2	5.2	6.3	7.6	8.9
40	0.2	0.9	1.6	2.3	3.2	4.1	5.1	6.2	7.5	8.8
30	0.2	0.8	1.5	2.3	3.1	4.0	5.0	6.1	7.3	8.7
20	0.1	0.7	1.4	2.2	3.0	3.9	4.9	6.0	7.2	8.5
10	0.1	0.7	1.4	2.1	2.9	3.8	4.8	5.9	7.1	8.4
0	0.0	0.6	1.3	2.0	2.8	3.7	4.7	5.8	7.0	8.2
SENSOR RESPONSE	0	100	200	300	400	500	600	700	800	900

a. Use for: Precise sensor reading at 14.7 psia (sea level). Total pressures of 14.7 to 18 psia (0 to 7.5 feet depth).

90	0.5	1.1	1.7	2.4	3.2	4.0	4.9	5.9	7.0	8.1
80	0.4	1.0	1.7	2.4	3.1	3.9	4.8	5.8	6.9	8.0
70	0.4	1.0	1.6	2.3	3.0	3.8	4.7	5.7	6.8	7.9
60	0.3	0.9	1.5	2.2	3.0	3.8	4.6	5.6	6.6	7.8
50	0.3	0.8	1.5	2.1	2.9	3.7	4.6	5.5	6.5	7.7
40	0.2	0.8	1.4	2.1	2.8	3.6	4.5	5.4	6.4	7.5
30	0.2	0.7	1.3	2.0	2.7	3.5	4.4	5.3	6.3	7.4
20	0.1	0.7	1.3	1.9	2.7	3.4	4.3	5.2	6.2	7.3
10	0.1	0.6	1.2	1.9	2.6	3.4	4.2	5.1	6.1	7.2
0	0.0	0.5	1.1	1.8	2.5	3.3	4.1	5.0	6.0	7.1
SENSOR RESPONSE	0	100	200	300	400	500	600	700	800	900

b. Use for: Total pressures of 18 to 100 psia (7.5 to 190 feet depth.

The pCO_2 can be derived from the sensor's ANALOG OUTPUT to within the accuracy limits determined by the sum of 6% of reading and 0.1 mm by using Tables 3.1 and 3.2 for helium and air respectively.

The accuracy of the pCO_2 derived from the sensor's response by applying the linearization expression (Equation 3.2) and the Pressure Correction Factor (Figure 3.2), can be evaluated by examining Figure 3.4, which compares seven calculated values with the actual levels of pCO_2 in helium.

From Figure 3.4 it can be seen that the computed pCO_2 compares very favorably with the actual pCO_2 over the complete range of total pressure (up to 600 psia) and pCO_2 (up to 10 mm).

3.4 Response Time of the Instrument

The response of the sensor as a function of time to a step change in the pCO_2 is illustrated in Figure 3.5.

This figure shows two separate measurements of 3.4 mm of CO_2 in air at a total pressure of 14.7 psia. The 0 to 90% response time for both increasing and decreasing levels of pCO_2 is about 40 seconds. The discrete nature of the trace is a result of the DVM-type of measurement cycle (see Section 2.2) used by the sensor--in which the output is updated every 10 seconds to indicate the latest reading. The response time is independent of pCO_2 level and will not change unless the dust filter in the sampling line becomes blocked. The response time has only been measured at 14.7 psia but is not expected to be dependent on the total pressure.

Both the physical and performance characteristics of this pCO_2 sensor are summarized in the SPECIFICATIONS.

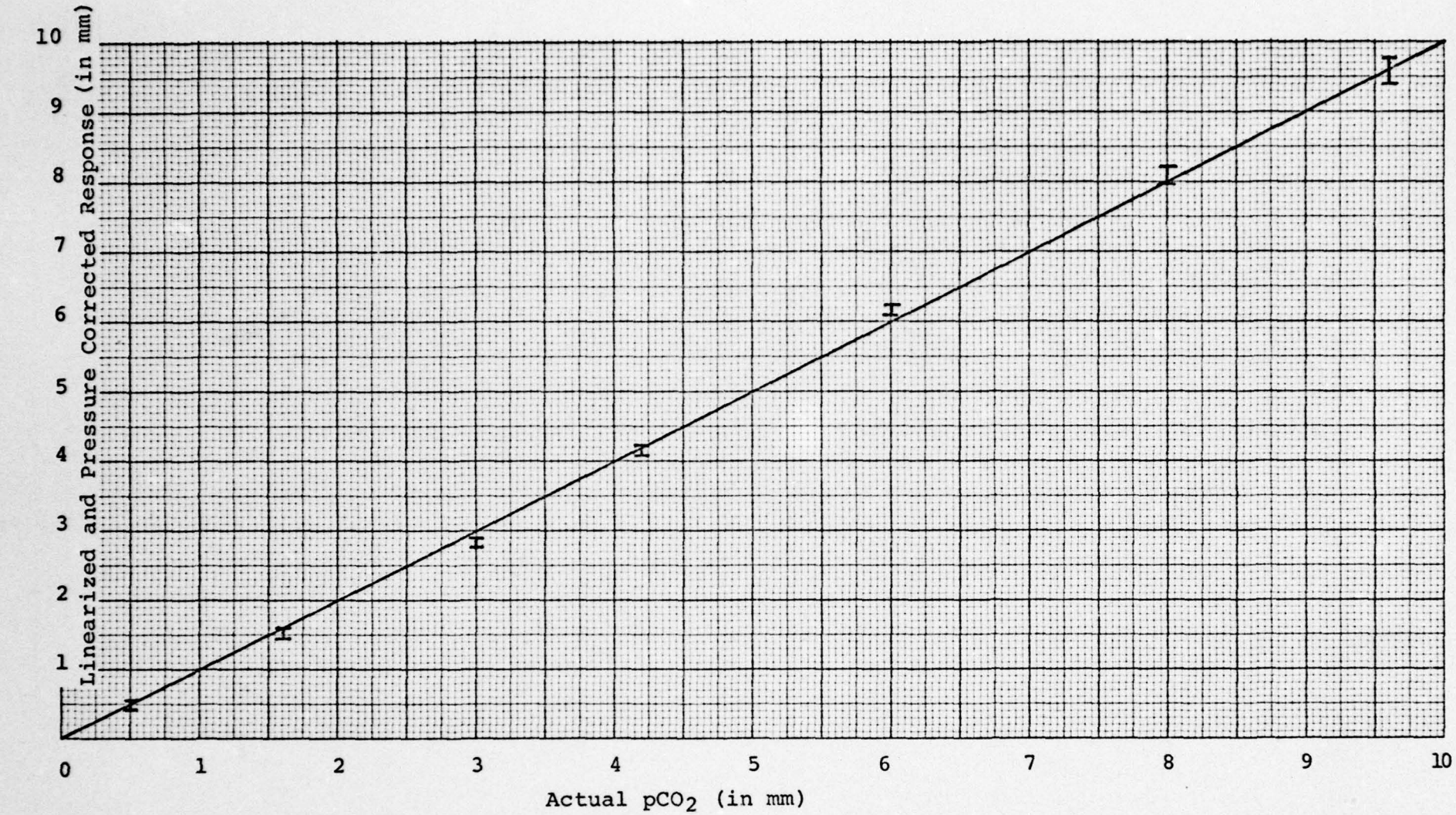


Figure 3.4. Equivalent sensor response for CO_2 in helium derived by applying the linearization expression (Equation 3.2) and the Pressure Correction Function (Figure 3.2) to the curves in Figure 3.1 as a function of the actual pCO_2.

I - represents the spread in derived values over the complete range of total pressure (14.7 to 600 psia).

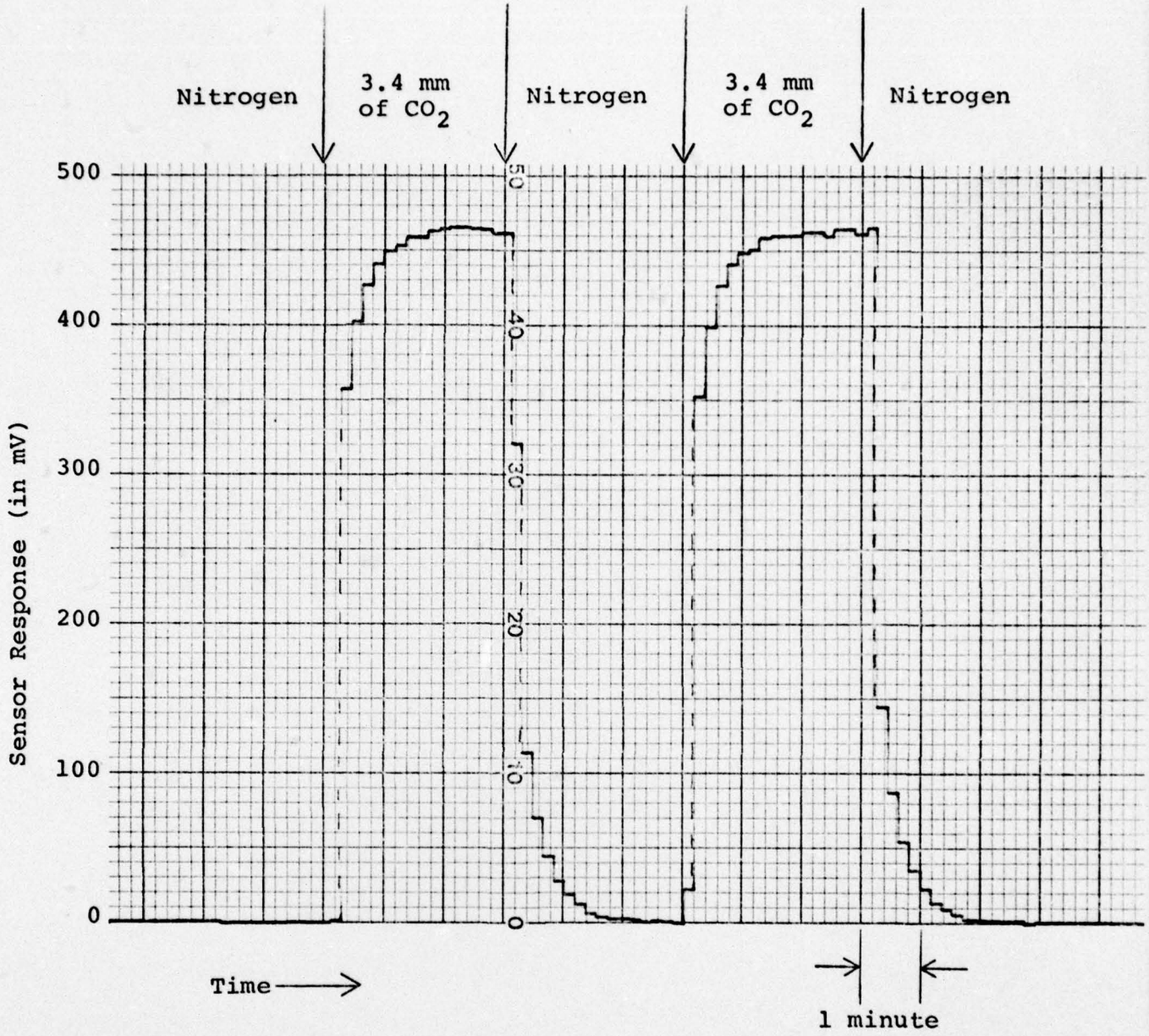


Figure 3.5. Response of the pCO_2 sensor as a function of time for 2 sequential measurements of 3.4 mm of CO_2 in air at a total pressure of 14.7 psia (sea level).

3.5 SPECIFICATIONS

Item	Value	Unit
1 PARTIAL PRESSURE OF CO_2 (pCO_2)		
1.1 RANGE	0.1 to 10	mm of Hg
1.2 ACCURACY dependence on TOTAL PRESSURE. (See Section 4 for more details.)		
(1) SPAN accuracy Examples of the maximum systemmatic error over the full range of total pressure of Helium for a one time calibration of CO_2 in:		
Helium at 14.7 psia	-3 to +15	% of reading
Air at 14.7 psia	-8 to + 8	% of reading
Helium at 150 psia	-8 to + 8	% of reading
(2) ZERO stability (at low values of pCO_2). Zero changes linearly with total pressure at a rate of:	-0.02	mm per 100 psia
1.3 ACCURACY dependence on TEMPERATURE		
(1) SPAN accuracy - temperature coefficient (determined by the Gas Law)	-0.3	% reading per °C
(2) ZERO stability - temperature coefficient (maximum)	-0.01	mm per °C
1.4 ACCURACY dependence on AGING of the unit. Predicted maximum (provided optical transmission does not decrease by more than 70%).		
(1) SPAN accuracy	±5	% reading per year
(2) ZERO stability	±0.2	mm per year

SPECIFICATIONS (Cont'd)

Item		Value	Unit
1.5	NOISE LEVEL		
(1)	Optical limit - as delivered - noise will increase proportionally to any loss of optical transmission	≤0.05	mm of Hg peak to peak
(2)	Electronic contribution	≤3	% of reading peak to peak
1.6	LINEARITY		
	Response to CO_2 is non-linear, being 2.6 times more sensitive to small changes in pCO_2 at low concentrations than at full scale.		
1.7	TIME RESPONSE		
(1)	Sensor output updates every	10	seconds
(2)	0 to 90% response time (for both increasing and decreasing pCO_2)	≤40	seconds
2	FLOW RATE OF SAMPLED GAS		
	Internal sample pump runs at:	100	milliliters per minute
3	MAXIMUM AMBIENT CONDITIONS		
3.1	Total Pressure - absolute maximum	600	psia
3.2	Rate of change of total pressure (maximum)	45	psi per minute
3.3	Temperature Range	40 to 100	°F
3.4	Humidity Range	≤95	% relative humidity

SPECIFICATIONS (Cont'd)

Item		Value	Unit
4 READ-OUT			
4.1 Meters:	Scale graduations (0 - 10 mm)	0.25	mm intervals
	Under range	-0.75	mm intervals
	Over range - to	14	mm reading
	Notes: - (1) Meter may be rotated through 90°. (2) Needle is offset up scale by 0.06 mm to correct for an electronic zero error.		
4.2 Analogue:	Nominal pCO_2 of 10 mm of Hg.	1.0	volts
	Source impedance	1000	ohms
	Notes: - (1) A zero offset in the electronics produces a (fixed) zero error of -	-0.015	volt
	(2) Electrical return wire is grounded to the chassis.		
5 MECHANICAL			
5.1	Physical size	6.5 x 7.5 x 14	inches
5.2	Weight (approx.)	10	pounds
5.3	Mounting: 4 holes in the base - tapped for ¼ x 20 screws.		
	Note: - Unit may be mounted in any orientation.		
6 ELECTRICAL POWER REQUIREMENTS			
	Nominal	28	volts D.C.
	Absolute minimum	25	volts D.C.
	Maximum continuous	32	volts D.C.
	Note: - Power return wire is electrically isolated from the chassis.		

SPECIFICATIONS (Cont'd)

	Item	Value	Unit
7	LIFE EXPECTANCY - Anticipated		
	Continuous use	>10,000	Hours
8	MAINTENANCE - Is minimal		
	Replace dust filers (quantity 2)	as required	
	Silica gel (to protect meter movement) - check color	as required	
9	WARM UP TIME		
	Time to read the pCO_2 of gas in the sample cell:		
	to an accuracy of 90%	0.5	minutes
	to within the stated accuracy	5	minutes

4. COMPONENT DEVELOPMENT AND DESIGN CRITERIA

4.1 Summary

All objectives of the program have been satisfied. In the electronic area, desirable components have been evaluated for their compatibility with the wide pressure range. Circuits have then been designed whose performance is not affected by total pressures up to 600 psia and which use components that do not require any screening to ensure their correct operation at high pressure. In the mechanical area, these include such items as developing and testing a suitable infrared source, infrared detector and miniaturized sample cell, as well as identifying and testing a suitable electric motor, small gas sampling pump, solenoid valves and miniature metal bellows. These components have then been integrated into a single optical-mechanical assembly which, together with the electronics, has been extensively tested over the required range of total pressure of 15 to 600 psia.

4.2 Mechanical Components

Both the infrared source and infrared detector have been packaged in small helium leak-tight enclosures. The reasons for this are to:

- Make the sample cell's volume small to increase both the sensitivity (by increasing the fractional volume modulation) and response time.
- Remove CO_2 from the otherwise uncontrolled optical path outside the sample cell.
- Protect sensitive items (such as fine filament wire and infrared detector) from exposure to corrosive materials such as salt.
- Prevent water condensation on the thermoelectrically-cooled infrared detector.
- Maintain a constant and relatively low thermal conductivity-type gas in contact with the filament and (cooled) infrared detector.

Particular care has been taken in testing the integrity of the infrared source and detector packages against helium penetration. In particular, the interior of each package fabricated was connected to a sensitive helium leak detector and 600 psia of helium repeatedly applied to the exterior housing. Helium penetration, if at all, of both packages finally selected was less than the leak detector's threshold sensitivity of 10^{-10} standard ccs per second and is therefore insignificant.

However, two very significant problems were experienced with 2 of the fabrication steps. The first of these was the final step in the fabrication of the infrared detector which was to electron beam weld the sapphire window assembly to the header. The electron beam welding technique was selected for this step because the infrared detector cannot be safely exposed to temperatures in excess of 70° C. The header must be made from a high thermal conductivity material to conduct heat pumped by the thermoelectric cooler (used to maintain the PbSe detector 20° C below ambient). Silicon bronze was used initially because the electron beam welding vendor was confident he could weld this to stainless steel or kovar and furthermore, the thermal conductivity of silicon bronze was acceptable. Subsequent testing of electron beam welded test pieces showed that helium leak-free joints could not be consistently reproduced, and the silicon bronze was not a suitable material for electron beam welding in this application. This problem was solved by high temperature brazing a stainless steel sleeve to a copper header before mounting the thermoelectric cooler. The final fabrication step was then to electron beam weld the stainless steel flange on the sapphire window assembly to the stainless steel sleeve on the header.

The second problem arose with the use of low melting point silver solders in fabrication of the infrared source. The metallurgical property of these solders was found to change with a combination of time and repeated pressure cycling between 15 and

600 psia, so that they eventually permit gross helium penetration. This problem was solved by redesigning the infrared source to eliminate the low melting point solders and use only electron beam welding and brazing processes.

The filament of the infrared source is wound with 0.005 inch diameter nichrome wire and runs at about 600° C at which temperature it should last indefinitely. A duplicate of the filament installed in the unit was set upon life test and cycled on for 21 hours and off for 3 hours. Its resistance was measured after 12,000 hours of operating time and found to be unchanged (within the measurement error of 2%). The filament was still working when the test was stopped after 18,000 hours.

The sample pump is a commercial unit ideally suited to this application and is mounted along side of the metal bellows (to be driven by the electric motor). The brushless DC motor is made by Siemens and has a life expectancy of 20,000 hours at a torque of 1.4 oz-inches at 55° C. Since the maximum torque required by our application is less than 0.21 oz-inch the life of the motor should be extended further.

The electro-formed nickel bellows used to produce the volume modulation is manufactured by the Servometer Corporation. Since the maximum stroke recommended for infinite life with a confidence level of 100% is 0.107 inches and the present design application calls for a maximum deflection of 0.040 inch, there is no reason to expect failure of the bellows due to fatigue.

Two miniature solenoid actuated valves are used to isolate a sample of gas in the sample cell. Should a failure cause the valves to remain sealed at a time when the total pressure is changing, the metal bellows has been protected by adjusting the spring loading of the valve plungers so that they will leak if the pressure differential exceeds about 40 psi. The valves are

attached to the sample cell in opposite senses allowing for total pressure changes in either direction. In addition, one valve is always open to the surroundings when the power is off so that again changes in total pressure cannot produce damaging pressure differentials between the sample cell and surroundings.

4.3 Electronic Components

All electronic components and critical circuits have been successfully and repeatedly pressure-cycled well beyond the sensor's maximum operating pressure of 600 psia of helium. Since the sensor may see use in an environmentally severe atmosphere such as a Personnel Transfer Capsule, where condensation of salt-ladened moisture on the electronics is likely to occur, the most susceptable circuit (namely the sample and hold module) has been evaluated extensively. The sample and hold circuit (and 3 such modules are used) uses a 10^{10} ohm resistor. Samples of this circuit were vacuum potted in Stycast 2651 epoxy and immersed in salt water at 60° C for 4 months. No degradation in the performance of the sample and hold was observed. Subsequently the sample and hold modules as well as the DC-to-DC power converters (standard Datel units purchased unpotted) which are installed in the pCO_2 sensor were vacuum potted with Stycast 2651 epoxy.

None of the electronic components of the types used in this gas sensor have failed as the result of exposure to total pressures up to 700 psia. The types of packages used without trouble are

Semiconductors:

- Plastic package - integrated circuits
  - discrete transistors and diodes
  - power transistors
  - optical couplers
  - zener diode type of transient suppressor
- Glass/Ceramic - rectifier diodes

Resistors: metal film
carbon composition

Capacitors: polycarbonate film
monolithic ceramic
disc ceramic
small dipped tantallum electrolytics.

5. REFERENCES

Williams, K.G., (1973)

Investigation of the Feasibility of an NDIR Technique to Detect CO_2 in a Hyperbaric Gaseous Environment. Andros Final Report ARFR-56 on Contract No.N00014-73-C-0185 for the Office of Naval Research.